Capítulo 8

De GARDGuide

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8.0 Monitoreo

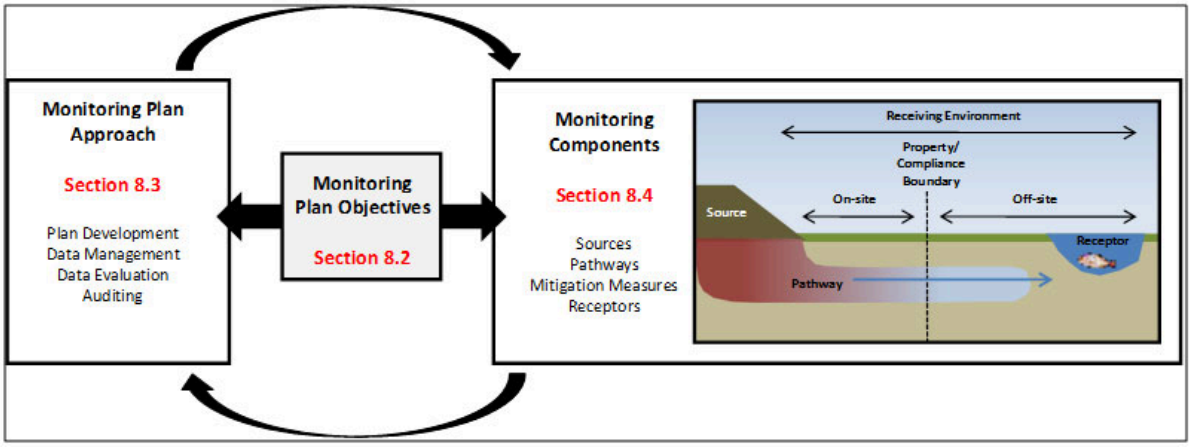
8.1 Introducción

El monitoreo es el proceso de recopilar información de manera rutinaria, sistemática y deliberada para su uso en la toma de decisiones de gestión. El monitoreo de la mina caracteriza los cambios ambientales provocados por las actividades mineras para evaluar las condiciones en el sitio y los posibles impactos en los receptores. El monitoreo incluye tanto la observación (por ejemplo, el registro de información sobre el medio ambiente) como la investigación (por ejemplo, estudios manipulativos como pruebas de toxicidad donde se controlan las condiciones ambientales). El monitoreo para evaluar la eficacia de las medidas de mitigación para minimizar los efectos de los procesos perjudiciales para el medio ambiente, como la ARD, y la implementación de ajustes a las medidas de mitigación según sea necesario es un ejemplo del uso del monitoreo en la toma de decisiones de gestión.

El desarrollo de un programa de monitoreo de ARD en un sitio minero comienza con la revisión del plan de la mina, la ubicación geográfica y el entorno geológico. El plan de la mina proporciona información sobre la ubicación y magnitud de las perturbaciones superficiales y subterráneas, los procedimientos de procesamiento y molienda de minerales, las áreas de disposición de desechos, los lugares de descarga de efluentes, las extracciones de agua subterránea y las desviaciones de agua superficial. Esta información se utiliza para identificar las fuentes de ARD, las posibles vías de liberación de ARD al entorno receptor, los receptores que pueden verse afectados por estas liberaciones y la posible mitigación que puede ser necesaria. Debido a que la extensión espacial de un programa de monitoreo debe incluir todos estos componentes, a menudo se requiere un enfoque de cuenca hidrográfica (incluidas las aguas subterráneas) para el monitoreo de ARD en un sitio minero. El monitoreo se realiza en todas las etapas del desarrollo del proyecto, desde la etapa preoperativa hasta la etapa posterior al cierre; sin embargo, durante la vida de una mina, los objetivos, los componentes y la intensidad de las actividades de monitoreo cambiarán.

En este Capítulo 8 se presentan las directrices y herramientas para establecer un programa de monitoreo en sitios mineros con potencial de ARD, NMD y SD. Primero se analizan los aspectos generales del monitoreo y luego se analiza el monitoreo específico de las fuentes de ARD más adelante en este capítulo. La orientación genérica proporcionada en este capítulo se puede utilizar para desarrollar enfoques de monitoreo específicos del sitio para evaluar la contaminación, los efectos y los impactos. La orientación proporcionada tiene como objetivo promover un programa de monitoreo que satisfaga las responsabilidades corporativas de una empresa y su compromiso con la minería sustentable, las necesidades regulatorias, el deseo de las partes interesadas de obtener información relevante y útil, y los requisitos de gestión de información relevante y significativa para respaldar la toma de decisiones ambientalmente apropiada y rentable. La Figura 8-1 describe la organización del capítulo. Primero se analizan los objetivos y el desarrollo de un plan de monitoreo, seguido de un análisis del monitoreo dentro de cada uno de los componentes.

Figura 8-1: Organización del capítulo de seguimiento



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8.2 Objetivos del seguimiento

El monitoreo permite a una empresa minera medir el éxito en el cumplimiento de los objetivos corporativos relacionados con la minería sustentable, la mejora continua del desempeño ambiental y social y la minimización de los impactos ambientales. Las autoridades regulatorias también pueden imponer requisitos de monitoreo como condición para desarrollar, operar o desmantelar un sitio. Los permisos mineros describen protocolos específicos de recopilación de datos y presentación de informes, a menudo con un enfoque en los puntos de descarga al medio ambiente receptor. También se pueden realizar compromisos de monitoreo con las partes interesadas o las agencias de crédito como parte de la "licencia social" para operar una mina o como condición de financiamiento. Muchas comunidades tienen representantes que están muy interesados en revisar los planes y datos de monitoreo ambiental. Fundamentalmente, la responsabilidad corporativa, el cumplimiento regulatorio o el acuerdo de las partes interesadas pueden ser los objetivos principales de un programa de monitoreo; sin embargo, los objetivos subyacentes o el propósito de la información obtenida de estos programas a menudo son proteger la salud humana y el medio ambiente.

Al comienzo de un programa de monitoreo se deben establecer objetivos bien definidos. Los objetivos específicos relacionados con la protección ambiental contra la liberación de ARD pueden incluir lo siguiente:

- Caracterización de las condiciones actuales (de referencia): este monitoreo está diseñado para caracterizar las condiciones ambientales de referencia (físicas, químicas y biológicas) con las que se medirán los cambios resultantes de la minería. Los ecosistemas no están totalmente libres de COI antes de una perturbación. Por ejemplo, los metales y metaloides se encuentran de forma natural en el medio ambiente (por ejemplo, agua y sedimentos) y en los tejidos biológicos, en particular en las áreas mineralizadas (es decir, donde se lleva a cabo la minería). Las condiciones de referencia también pueden verse afectadas por la minería histórica u otras actividades antropogénicas no relacionadas con la minería. Durante el monitoreo de referencia, se identifican las áreas particularmente sensibles a los cambios.
- Confirmation of ARD Potential – This monitoring takes place during the development phase and involves solid phase analyses and leach testing (static and kinetic) being conducted to assess the ARD potential of waste and ore materials (see Chapters 4 and 5). These tests may continue during operation. Monitoring is conducted to confirm the potential for ARD derived from the testing program.
- Detect or Predict Onset of ARD – This monitoring is designed to detect the onset or predict future release of ARD as early as possible to allow implementation of mitigative measures. Monitoring may include direct or indirect measures of ARD release (e.g., direct - collection and analysis of waste material seepage and runoff; or indirect - measurement of temperature and oxygen profiles within a waste rock facility as a measure of sulphide oxidation). Monitoring data may be required to validate or calibrate predictive models (see Chapter 5).
- Verification of Expected Behaviour – This monitoring during operations is designed to confirm the expected environmental behaviour of mine materials, as determined from characterization and prediction efforts (see Chapters 4 and 5). Monitoring allows for detection of unexpected behaviour so appropriate corrective actions can be taken.
- Assess Fate and Transport of Constituents – This monitoring is designed to characterize physical or geochemical conditions to evaluate the rate of movement of COIs through the receiving environment.
- Assess Impacts to the Receiving Environment – This monitoring is designed to characterize current conditions to evaluate impacts to the environment. A distinction should be noted between effects, basically alterations which may or may not be harmful (e.g., changes in water or sediment quality) and impacts, which are environmentally harmful. Impacts adversely affect the utility, viability, and productivity of a population of organisms, not just individual organisms. However, in the case of humans or endangered species, impacts would also apply to individual organisms.
- Environmental Management – This monitoring is designed to assess the performance of waste management practices, including engineered designs to reduce, prevent, control, or treat ARD and strategies put in place for proper waste disposal (e.g., waste rock segregation).

Monitoring objectives may change during the life of a monitoring program. Objectives should be reviewed and updated, as required, as part of the audit process (see Section 8.3.5). A statement of clear objectives is required to direct and focus a monitoring program and to avoid expensive and unnecessary data collection efforts.

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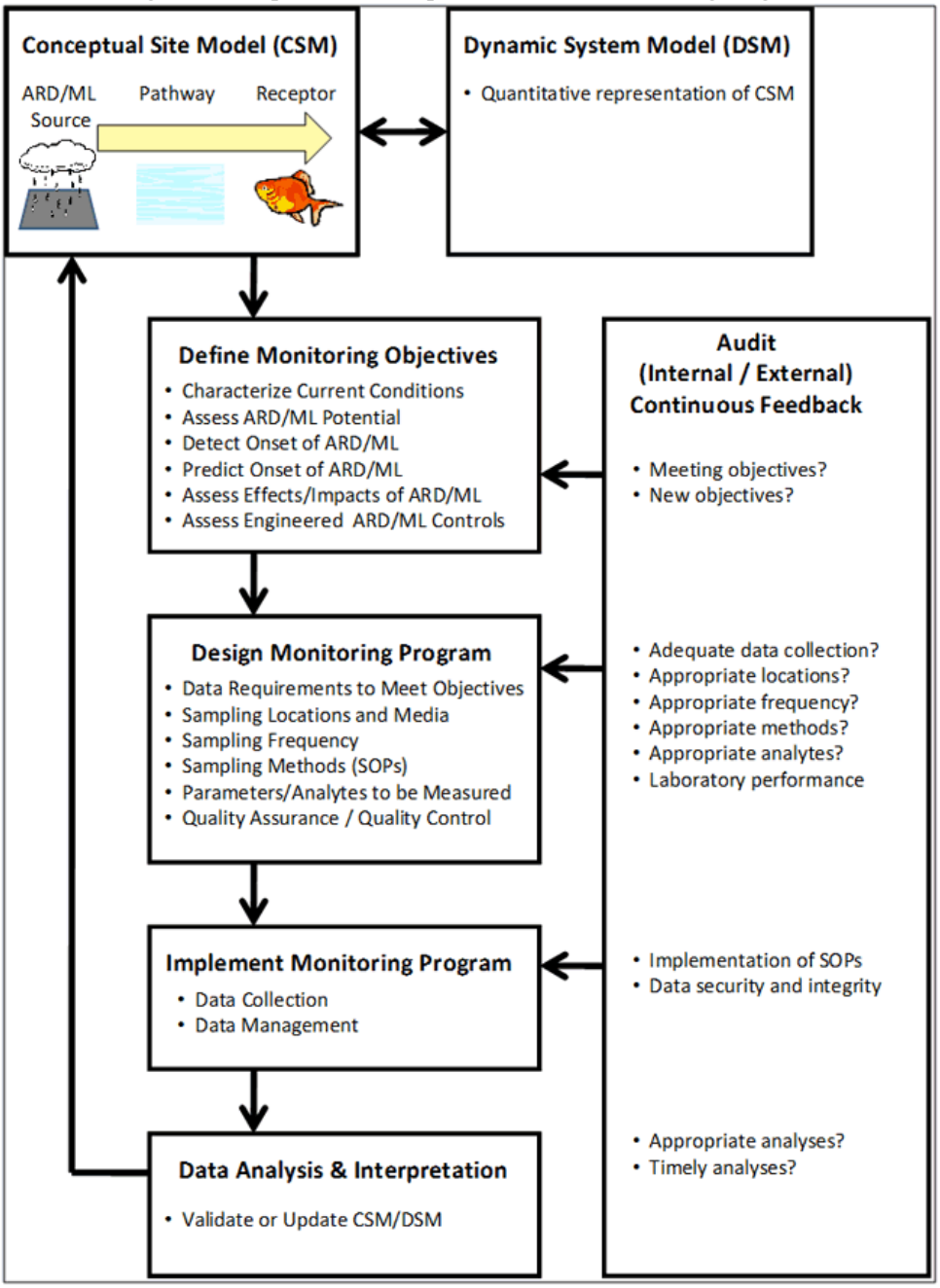
8.3 The Acid Rock Drainage Monitoring Approach

The monitoring program implemented at a mine site is determined by the monitoring objectives. Effective monitoring balances comprehensiveness, necessity, and monetary costs. The monitoring program is site-specific and takes into consideration the phase of project development and the sensitivity of the surrounding environment and community. This Section 8.3 presents the steps in development of a monitoring program (Figure 8-2).

Figure 8-2: Steps in the Development of an ARD Monitoring Program



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8.3.1 Conceptual and Dynamic System Model Development

The conceptual site model (CSM) (see Chapter 4 and Figure 4-4) provides the framework for development of an ARD monitoring program. The CSM is a hypothesis that incorporates site data to assess future or current environmental impacts from a mining operation. The CSM integrates geologic, hydrologic, chemical, biological, and climatic information to describe the release, transport, and fate of constituents at a mine site. It should involve both temporal and spatial components and should be reviewed and agreed to by regulatory agencies and other stakeholders before beginning field or laboratory studies. Environmental conditions at similar sites can assist in identifying potential shortcomings and pitfalls and help focus the CSM as much as possible. CSMs are dynamic and should be updated as additional project information becomes available.

The CSM is used to identify the ARD sources, pathways, and receptors for inclusion in the monitoring program (Table 8-1).

Table 8-1: Monitoring Sources, Pathways, and Receptors

Source - Chemical	Pathway – Physical	Receptor – Biological
Waste rock	Air	Aquatic life
Tailings	Vadose zone	Terrestrial wildlife
Ore stockpile	Groundwater	Vegetation
Heap leach pile	Surface water - sediment	Humans
Underground workings (walls)		
pit (walls)		

The primary sources of ARD are mine and process waste, ore, and the disturbances resulting from ore extraction. The primary pathway to the environment for constituents (acidity, metals and metalloids) released from these sources is water. Transport may occur by way of groundwater, surface water, or infiltration through the vadose zone. Sediment and air pathways are typically of lesser importance. Because water is the primary pathway for metals and acidity, aquatic resources are generally the primary receptor of interest.

The CSM provides the framework for development of a dynamic system model (DSM). The DSM integrates the components of the CSM (i.e., sources, pathways, and receptors) and identifies their inter-relationships. The DSM quantifies the processes that control the release (e.g., sulphide oxidation), transport, and uptake of COIs. Because of the importance of water with respect to all of these processes, a site-wide water balance is a primary component of the DSM. The DSM is calibrated to current conditions and then used to predict constituent fate and transport. DSM may also be used to evaluate the effectiveness of mitigative measures. The DSM will highlight uncertainties and data gaps and therefore can be used to identify key components of the monitoring program. The monitoring program may include collection of data to verify or improve the accuracy of model predictions. Sensitivity analyses may be conducted to identify key input parameters to the DSM for inclusion in the monitoring program.

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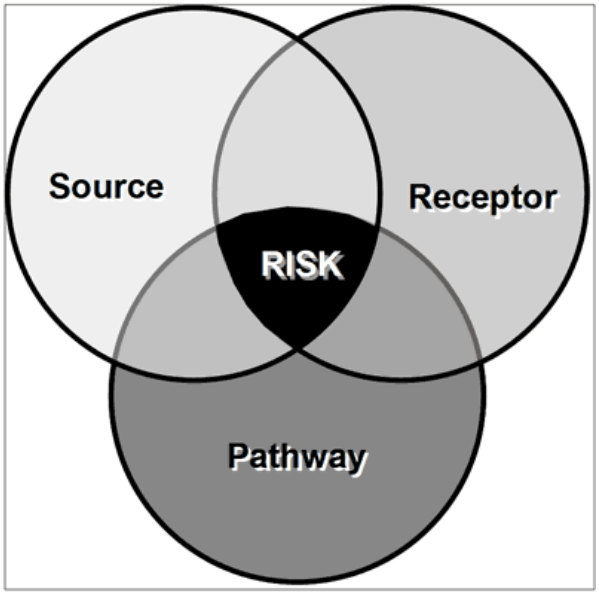
8.3.2 Risk Based Approach to Monitoring Program Development

A mine site monitoring program will include monitoring of both on-site facilities and the receiving environment. On-site monitoring will include monitoring of facilities identified as having the potential to generate ARD (i.e., sources). The scope of the source monitoring program, including frequency and extent, should follow a risk-based approach that considers the probability and consequences of ARD generation at a source.

A risk-based approach to monitoring evaluates the relationships between the ARD sources, the organisms that live in the environment that receives the ARD products, and the pathways that link the discharge source to the organisms to determine the potential for exposure. Risk (or exposure) can only exist if a stressor (or source), pathway, and receptor coincide (Figure 8-3). In this risk-based approach, the receiving environment is viewed as an ecosystem and the effluent is considered in relationship to that ecosystem. This means that the resident organisms, their habitat and ecology, and nature of how they are exposed to the stressor (or stressors) all need to be considered.

Figure 8-3: Conceptual Risk-Based Approach - Relationships Between the Contaminant Source, the Receptor, and the Pathway that Connects them



A risk-based environmental effects monitoring program seeks to identify the following:

- The pathways by which organisms may become exposed to an effluent
- The extent to which these organisms are likely to be exposed
- The effect or impact that exposure is likely to have on these organisms

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8.3.3 Monitoring Program Development

Development of an ARD monitoring program begins with an assessment of the likelihood that waste and ore materials will generate acid and leach metals. Source material characterization methods and the interpretation of characterization results are discussed in Chapters 4 and 5, respectively.

Water is often the focus of ARD monitoring programs because of its role in both the release and transport of ARD, its frequent beneficial use (e.g., drinking water and irrigation), and its function as a habitat for aquatic receptors. Monitoring programs include collection of data to assess water quality and movement. Water quality data are collected to evaluate compliance with standards and fate and transport. Water quality standards are defined as follows: "A water quality standard defines the goals of a water body by designating the use or uses to be made of the water, establishing criteria necessary to protect those uses, and preventing degradation of water quality through antidegradation provisions" (USEPA, 2003). Because water use may include human consumption or aquatic habitat, or both, water quality monitoring also provides information on possible impacts to receptors.

ARD monitoring programs often include collection of data to evaluate the sulphide oxidation process. Because there may be a lag time to the onset of ARD at a mine site, prudent environmental management includes an assessment of the stage of potential or actual ARD.

Development of a monitoring program must consider the climatic conditions at a particular site. The occurrence and distribution of rainfall at a site will dictate decisions regarding the timing of water sample collection. For example, in arid regions, collection of water samples may be scheduled to occur concurrent with rainfall events instead of at equally spaced intervals over time. Also, in arid regions, groundwater may be the primary constituent pathway and therefore the focus of water monitoring. Climatic conditions will also affect the rate of evolution of ARD (i.e., ARD evolution may be slower at low precipitation sites and in cold climates) which will affect decisions regarding the frequency and locations of sample collection.

This Section 8.3 presents the information included in a mine monitoring program applicable to all components of the CSM (i.e., ARD source, pathway, mitigation, and receptor). This mine monitoring information is typically included in the sampling and analysis plan (SAP) or QAPP for a site. Detailed discussions specific to monitoring of each component are presented in Section 8.4.

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8.3.3.1 Data Requirements

The data collection activities required to fulfill the monitoring objectives must first be identified. These will define the media that will be sampled (e.g., water, gas, or sediment). Table 8-2 lists activities common to ARD monitoring programs and the rationale for each activity.

Table 8-2: Common ARD Monitoring Components

Type	Information	Rationale
Climatic	Rainfall	water balance input
	Evaporation	water balance input (pit)
	Temperature	water balance
	Humidity	water balance
	Wind direction	assess ARD process
	Wind speed	assess ARD process
	Snowpack	water balance
Hydrology	Surface water flow	calculation of contaminant loading
		aquatic habitat assessment
		site or facility water balance input
	Surface water quality	characterize in situ conditions (baseline)
		assess ARD/ML source/process
		evaluate COI fate and transport
		habitat information for receptor exposure and effect/impact assessment
	Sediment quality	characterize in situ conditions (baseline)
		evaluate COI fate and transport
		habitat information for receptor exposure and effect/impact assessment
Hydrogeology	Groundwater flow	evaluate COI fate and transport
		site or facility water balance input
	Groundwater quality	characterize in situ conditions (baseline)
		evaluate COI fate and transport

		assess ARD/ML source/process
Biological	Aquatic receptors	characterize baseline conditions
		assess COI exposure and effects/impact
	Habitat	receptor exposure and effects/impact assessment
Geochemical	Chemical composition	assess ARD/ML potential
	ABA	assess ARD/ML potential
	Leach testing	assess ARD/ML potential
	Mineralogy	assess ARD/ML potential
Gas	Gas transfer	assess ARD process

ML – metal leaching

COI – constituent of interest

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8.3.3.2 Statistical Considerations

Fulfillment of the objectives of the monitoring program will include use of appropriate statistical and other data analyses. To assess effects or impacts, exposure (i.e., downgradient) data are compared to reference (i.e., upgradient) data to determine if there is a difference. Compliance monitoring may require that mean or peak concentrations not exceed a certain limit within a prescribed confidence limit. This Section 8.3.3.2 presents statistical concepts relevant to the design of an ARD monitoring program. Monitoring design should include evaluation of the statistical methods that will be used in data analysis.

Sample Variation - Determination of sample variation is key to design of an efficient monitoring program. The three forms of sample variation are as follows:

- Spatial – measurable differences between stations
- Temporal – measureable differences within a station between sampling periods
- Instantaneous – measurable differences within a station during the same sampling period (includes “real” variation as well as analytical and field errors)

Variation is determined by taking multiple samples (over time, space, or both time and space) and examining their frequency distribution. Collection of single samples assumes no instantaneous variability. Collection of replicate samples is required to assess instantaneous variability. Differences between sites (spatial variation), the fundamental basis of an impact assessment, can be determined only when differences within a site (instantaneous variation) are known.

Frequency Distribution - Sample variance and the shape of the frequency distribution must be considered in monitoring program design because sample variance and the shape of the frequency distribution determine the number of samples needed to reach a predetermined confidence level for estimates of mean and peak values. Selection of appropriate statistical procedures depends on the nature of the distribution.

Stratification – Strata are factors that may influence the mean or variance of a parameter and may be evident by a bimodal or multimodal frequency distribution. Efficient sampling designs are stratified according to the dominant pattern of variation. For example, monitoring of ARD impacts to a stream may be seasonal or flow related.

Autocorrelation - Autocorrelation (serial dependence) must be considered to determine optimal sampling frequency, especially when mean concentrations are required. Accurate determination of the mean with the fewest number of samples requires that the sampling frequency be low enough so that each sample is independent of the previous sample. For systems with low autocorrelation, sampling frequency must be high enough to achieve the desired confidence limits of the mean. High frequency sampling should be conducted during preliminary studies to determine the degree of autocorrelation. These data will also indicate the duration of peak or minimum values, which may be of interest in assessing environmental effects or impacts.

At mine sites where ARD is occurring, or suspected of occurring, an intensive preliminary sampling program that includes the steps listed in Table 8-3 is recommended (MEND, 1990).

Table 8-3: Preliminary Intensive Sampling Program

Step	Evaluation	Description
1	Preliminary stratification	Identification of all factors that might influence the mean or variance of ARD parameters. Selection of temporal and spatial strata.
2	Cofactors	Identification of factors that may influence the mean and variance of the data for inclusion in monitoring program (e.g., flow).

3	Instantaneous variation	Collection of 4 to 6 replicate samples for each strata (temporal or spatial).
4	Autocorrelation	Collection of numerous samples within each time stratum to evaluate short-term temporal variation and lag time between independent samples. Continuous monitoring of key parameters (pH and electrical conductivity) to correlate with other ARD parameters measured at shorter time intervals.
5	Frequency distribution and variance	Using the time interval between independent samples (Step 4), collect a minimum of 30 random samples during each time stratum to determine the frequency distribution (more than 30 samples are typically required for non-normal distributions).
6	Monitoring design optimization	Using the preliminary data and defined control criteria (e.g., confidence limits) optimize the monitoring program. Strata identified in Step 1 should be evaluated and reduced to those with unique means, variances and/or frequency distributions. Evaluate cofactor and variable/variable relationships to identify reduction in parameters. Determine sampling frequency from autocorrelation data.

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8.3.3.3 Sampling Locations

Collection of samples at the potential source of ARD provides information on the onset of ARD and the magnitude of constituent loading to the environment. Section 8.4.1 describes the types of samples (e.g., seepage, runoff, or supernatant) typically collected at different ARD sources.

Designs of receiving environment sampling locations for impact studies must consider the approach that will be used to determine if a measurable impact has occurred as a result of mining activities (Table 8-4). These approaches vary in the selection of premining or reference monitoring locations.

Table 8-4: Impact Assessment Sampling Location Designs

No.	Design Type	Name	Description
1	Spatial	Control-Impact (CI) or Upgradient-Downgradient	Spatial comparison between reference sites (upgradient) and potentially impacted sites (downgradient)
2	Temporal	Before-After (BA)	Temporal comparison between premining (baseline) and mining data
3	Spatial-Temporal	Before-After-Control-Impact (BACI)	Include both spatial and temporal comparisons (combination of 1 and 2)
4	Spatial	Gradient	Spatial comparisons along an identifiable contaminant gradient

The most robust study designs include a temporal and spatial component (i.e., Before-After-Control-Impact [BACI]) to compare nonimpact versus potentially impacted areas. Study designs that include control/reference stations (i.e., Control-Impact [CI] and BACI) are enhanced by the inclusion of multiple reference stations (MEND, 1997). Upgradient-downgradient designs are typically employed at mine sites to evaluate ARD release from primary sources.

Reference areas or locations serve as additional benchmarks (to baseline data) against which to compare sites exposed to COIs. Characterization of reference sites must be adequate enough to distinguish potential ARD effects from natural variability or trends at the regional scale, or both. Typically, reference areas or locations represent “the optimal range of minimally impaired conditions that can be achieved at sites anticipated to be ecologically similar” and should be acceptable by local stakeholders and appropriately represent reference conditions (Krantzberg et al., 2000).

The media to be sampled (e.g., solids, water, or biological) and methods of sample collection will influence the selection of sampling locations. Selection of sampling locations should consider the following (if applicable):

- Inclusion of compliance monitoring locations stipulated in permits and inclusion of upgradient stations as early warning of effects or impacts
- Colocation with historical sampling locations to allow for direct comparison and evaluation of temporal trends
- Colocation of samples for different media (e.g., sediment, water, benthic macroinvertebrates, plankton, or periphyton) as required for data analysis
- The number of locations required to ensure characterization of spatial variability
- Safe and easy access during all sampling periods

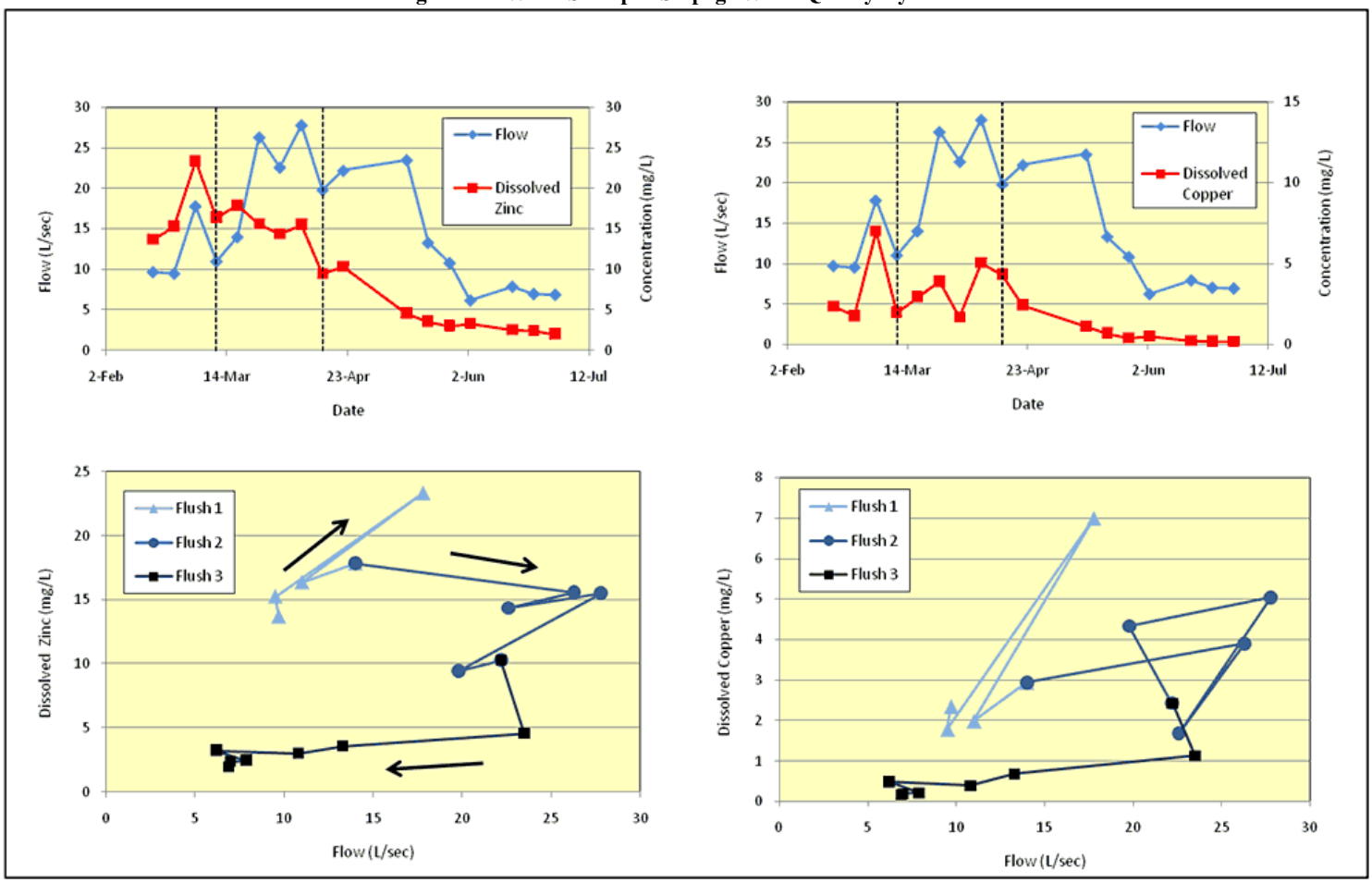
8.3.3.4 Sampling Frequency

Determination of the appropriate sampling frequency for ARD monitoring must consider temporal variability in acidity and metal release from sources related to climatic conditions. During prolonged dry periods or freezing conditions, sulphide oxidation products will accumulate within source materials. These dry periods are characterized by having sufficient water available to support sulphide oxidation, but insufficient water to flush the products of these reactions. “First flush” events (e.g., the first rainfall after a prolonged dry period, snowmelt, or a period of thawing) are generally characterized by high acidity and high metal loading. Runoff and seepage quality from ARD sources therefore will not only be a function of the composition of materials, but also the water contact time, precipitation or snowmelt event duration, position in hydrograph, and time since last flushing event.

Determination of sampling frequency must consider the climatic conditions at the mine site. For example, in low precipitation environments, seepage from waste rock piles may be intermittent. Seepage collection may therefore need to occur concurrent with rainfall events. Natural springs may also flow intermittently and therefore the timing of flow and water quality monitoring may be dependent on rainfall events.

Hysteresis Effect – Hysteresis describes the cyclic relationship between concentration and flow (rising versus stable or falling hydrograph). Accumulated sulphide oxidation products are flushed with the first flush event. Concentrations increase as infiltrating water contacts more surfaces. If flow stabilizes, concentrations will remain stable or decrease as stored oxidation products decline. Eventually, concentrations decrease with steady or rising flows due to declining reserves. At the end of the cycle, the source material is well rinsed and continued flushing only carries the ARD products being generated at the time (Figure 8-4). Maximum ARD loads are therefore generated during moderate to high flows that follow low flow periods (MEND, 1990).

Figure 8-4: Waste Stockpile Seepage Water Quality Hysteresis



Although fixed frequency sampling is often stipulated in mine permits for water quality and flow monitoring, fixed frequency may not satisfy the monitoring objectives, particularly if accurate mean or peak concentration values are required. Sampling frequency design should be based on the monitoring objectives that indicate the required accuracy of mean and peak values. The required accuracy level is based on the magnitude of the minimum changes or differences (i.e., variance) that must be detected (MEND, 1990). Accurate monitoring of peak concentrations may require intensive monitoring. The required accuracy, and therefore number of samples required, should consider the environmental risk associated with a short-term peak value.

“Efficient sampling programs are stratified according to the dominant pattern of variation in the data” (MEND, 1990). Seasonal stratification for monitoring of ARD sources is often appropriate. To capture the first flush event, the monitoring start date must be flexible and determined by the on-site operator. When monitoring ARD release to a stream, a flow-stratified frequency may be adopted. This method is appropriate when accurate determination of annual loading is required.

Continuous monitoring of water quality parameters or flow is a tool that should be considered to determine accurate average and peak values. Due to the hysteresis effect, a continuous monitoring device may be the only way to capture peak concentrations because peak concentration is a function of recent weather conditions as well as immediate rainfall and flow conditions (MEND, 1990). When possible, continuous measurement of ARD indicator parameters using probes (e.g., pH and electrical conductivity) represents the most accurate measurements of peak and average values. Although this approach may not be suitable for measurement of metals, correlations may be developed. Continuous measurements of water levels using a transducer allow for creation of a continuous flow record. For continuous monitoring devices, the time period over which data are read, averaged, and reported must be determined. At remote sites, installation of continuous monitoring devices may not be practical because of the possibility of breakdown, theft, or vandalism. System design must consider these issues. In such instances, employment of local personnel to perform monitoring activities may be an expedient alternative.

Monitoring frequency should consider the degree of autocorrelation. For both flow and water quality, slower changes in groundwater in comparison to surface water quality result typically in a shorter time period between surface water measurements than groundwater measurements. Increased frequency may be appropriate for groundwater wells located adjacent to surface water when groundwater levels show a surface water influence.

Baseline Data Collection - The potential for seasonal variability in background water quality, because of acidity and metal releases associated with historical mining or natural conditions (mineralized areas), should be considered during the baseline data collection.

The timing of sampling events should consider not only the potential for variability in ARD release, but also variability in receptor sensitivity (e.g., ARD release during early stages of fish development).

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8.3.3.5 Sampling Methods and Protocols

Selection of appropriate sampling methods and protocols will depend on data requirements and will consider factors such as site specific characteristics, permit requirements, and required accuracy and precision. Written SOPs should be developed and available for reference. SOPs ensure the following:

- Implementation of a uniform approach and methodology
- Continuity with changing personnel
- Use of standard field forms
- Inclusion of QA/QC procedures (e.g., decontamination)
- Use of correct sampling equipment
- Adherence to corporate health and safety requirements

Table 8-5 lists SOP references for typical data collection activities.

Table 8-5: Monitoring Activity Guidance

Monitoring Activity	Guidance Reference	Web Link
Water Quality Sampling	**ISO** 5667 - *Water Quality Sampling - Part 3: Guidance on the Preservation and Handling of Water Samples* (ISO, 2003)	http://www.iso.org/iso/iso_catalogue/catalogue_tc/catalogue_detail.htm?csnumber=33486
	USGS - *National Field Manual for the Collection of Water-Quality Data* (USGS, variously dated)	http://pubs.water.usgs.gov/twri9A
	ANZECC/ARMCANZ - Australian Guidelines for Water Quality Monitoring and Reporting (ANZECC and ARMCANZ, 2000)	http://www.mincos.gov.au/publications/australian_guidelines_for_water_quality_monitoring_and_reporting
	ACMER - *A Guide to the Application of the ANZECC/ARMCANZ Water Quality Guidelines in the Minerals Industry* (Batley et al., 2003)	http://www.acmer.uq.edu.au/publications/attachments/WQGTableofContents.pdf

Water Quality Sampling - Low Level Metals Analysis	**USEPA** - *Sampling Ambient Water for Trace Metals at EPA Water Quality Criteria Levels* (USEPA, 1996)	http://www.ecy.wa.gov/programs/wq/wastewater/method_1669.pdf
Groundwater Sampling	**USEPA** - *Ground-Water Sampling Guidelines for Superfund and RCRA Project Managers* (Yeskis and Zavala, 2002)	http://www.epa.gov/tio/tsp/download/gw_sampling_guide.pdf
	ISO 5667 - *Water Quality Sampling - Part 18: Guidance on Sampling of Groundwater at Contaminated Sites* (ISO, 2001)	http://www.iso.org/iso/iso_catalogue/catalogue_tc/catalogue_detail.htm?csnumber=29025
	NEPC - *Schedule B (2) Guideline on Data Collection, Sample Design and Reporting* (NEPC, 1999) (includes information on soil sampling)	http://www.ephc.gov.au/nepms
	AS/NZS - *Water Quality Sampling, Part 11: Guidance on Sampling of Groundwaters* (AS/NZS, 1998)	http://infostore.saiglobal.com/store/details.aspx?ProductID=387183
Surface Water Sampling	**ISO** 5667 - *Water Quality Sampling - Part 6: Guidance on Sampling of Rivers and Streams* (ISO, 2005)	http://www.iso.org/iso/iso_catalogue/catalogue_tc/catalogue_detail.htm?csnumber=34815
Gas Transfer	**MEND** - *Field Procedures Manual Gas Transfer Measurements* (MEND, 1993)	http://www.mend-nedem.org/reports/files/7.5.pdf
Tailings Monitoring	**MEND** - *Field Sampling Manual for Reactive Sulphide Tailings* (MEND, 1989)	http://www.mend-nedem.org/reports/categories-e.aspx?cat_id=10
Receptor Monitoring	**APHA/AWAA/WEF** - *Standard Methods for the Examination of Water and Wastewater*	http://www.apha.org/

	(23rd Edition) (APHA/AWAA/WEF, 2007)	
	ASTM - *Annual Book of ASTM Standards - Section 11 - Water and Environmental Technology* (ASTM, 2007)	http://www.astm.org/index.shtml

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8.3.3.6 Analytes

For all chemical analyses, the monitoring program should identify the analytes for all media of interest (e.g., water, sediment or mine waste) at each sampling location. The parameters typically of most relevance for water samples collected for ARD monitoring programs are the following: pH, (acidity or alkalinity, or both), electrical conductivity, and sulphate and metals of interest as determined for a particular site during characterization (Chapter 4). Sulphate, pH, and electrical conductivity are indicator parameters that are used to monitor the onset of ARD, as described in Chapters 2 and 4.

Determination of the analytes for water quality samples should consider the following:

- Relevant regulatory guidelines (e.g., aquatic life, potable water, antidegradation)
- COIs identified during predictive geochemical testing (see Chapter 4 and Chapter 5)
- Requirements for predictive geochemical modeling (i.e., comprehensive chemical analyses)
- Inclusion of analytes for QA/QC evaluations (e.g., major ions for calculation of ion balances)
- Inclusion of analytes that modify toxicity (e.g., pH, hardness, dissolved organic carbon)
- Analytical holding times (at remote sites, transport and analysis of samples within acceptable holding times may not be feasible)
- Appropriate parameter state (e.g., dissolved, total or total recoverable metals analysis; free, weak acid dissociable [WAD], or total cyanide analysis)
- Inclusion of chemicals introduced during mineral processing or extraction (e.g., nitrogen species from blasting agents)
- Inclusion of in situ field analyses (e.g., pH, redox, electrical conductivity, temperature, alkalinity, dissolved oxygen, turbidity)
- Inclusion of radiological parameters
- Cofactor or variable/variable relationships opportunities to reduce the analyte list

Water sampling SOPs should include information on appropriate sample containers, preservation methods, and storage times.

Guidelines for selection of parameters in receiving waters for early identification of a release are listed below (Maxfield and Mair, 1995):

- Fate and Transport – Are mobile (i.e., unlikely to be retarded in surface water and groundwater), stable, and persistent
- Baseline Conditions - Do not exhibit significant natural variability in background concentrations
- Analysis – Are easy to detect and not subject to significant sampling and analytical interferences
- QA/QC – Are common laboratory or field contaminants

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8.3.3.7 Laboratory Selection

Laboratory selection is a primary consideration in successful implementation of a monitoring program because of the laboratory's role in generation of an accurate and defensible data set. Issues for consideration in laboratory selection include the following:

- Location (shipping costs and sample delivery within holding times)
- Reporting limits (Reporting limits must be low enough to allow comparison to applicable guidelines/standards.)
- Scope of services (water analyses, geochemical testing)
- QA/QC (laboratory SOPs, level of QA/QC reporting)
- Service (turn-around times, electronic reporting, report customization, and responsiveness)
- Accreditation
- Cost

On-Site Laboratory Analyses – Two advantages of on-site analysis are favorable economics and improved decision-making capabilities due to rapid turn around. The required analytical precision and accuracy must be considered in the selection of any laboratory, including the decision to analyze samples in-house. An in-house laboratory may not be capable of analyzing key ARD parameters to the required levels of detection.

Analytical accuracy has sometimes been overemphasized as a priority in ARD monitoring. In reality, the day to day variations occurring in surface water are usually much greater than the results from an on-site laboratory versus a commercial laboratory (MEND, 1990). On-site analysis often allows for increased sampling frequency. Verification of on-site results can be achieved by submission of split samples to an accredited commercial laboratory. For some monitoring objectives, use of an on-site laboratory may not be appropriate (e.g., analysis of samples requiring high precision and low detection limits, sample analysis for regulatory reporting).

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8.3.3.8 Quality Assurance/Quality Control

The reliability of assessments made from a data set depends on the accuracy of the data set. To ensure collection of data of known and defensible quality, QA and QC operating procedures are implemented. Elements of a QAPP and specific information included for each are listed below (USEPA, 2001):

- Project Management – specific roles and responsibilities of the project team, personnel qualifications and training requirements, DQO,, and performance criteria
- Data Generation and Acquisition – SOPs for data collection, measurement and analysis, sample handling and custody, analytical methods, laboratory and field quality control activities (e.g., blanks, duplicates, laboratory control samples) and required control limits and corrective actions, instrument calibration and maintenance, and data management
- Assessment and Oversight – components and schedule for performance audits, response actions for deficiencies and nonconforming activities
- Data Validation and Usability – criteria for data review and validation

For water quality analyses, selection of a laboratory and appropriate analytical methods to achieve the required reporting limits is an important step in generation of a useful data set. When project requirements include very low trace metal reporting limits, appropriate field procedures must be employed to avoid sample contamination. The USEPA provides guidance on collection of ambient water samples using ultra-clean techniques for low-level metal analysis (USEPA, 1996).

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8.3.3.9 Health and Safety

Health and safety factors must be considered in the design and implementation of the monitoring program. For example, sampling should not be mandated (by managers or by regulatory authorities) when such activities could pose a danger to human health. It is mandatory nowadays that environmental managers develop and provide a budget for a health and safety plan before sampling is initiated.

Personnel tasked with collection of samples from source areas, in particular waste rock piles, should be aware of the potential for oxygen deficient conditions because of sulphide oxidation and carbonate neutralization reactions. Climatic conditions, including temperature differentials between air and waste rock facilities and sharp drops in barometric pressures, have resulted in outflows of oxygen-depleted air from a waste pile. Sampling locations should be sited in areas where there are no limitations to the mixing of out-flowing gases with the surrounding area. Further information on the air quality hazards associated with waste rock stockpiles is presented in Phillip et al. (2008) who describe the incident at the Sullivan Mine in British Columbia, Canada. Sampling of coal waste piles may require establishment of specialized health and safely protocols to address burning waste or the potential for spontaneous combustion. Similarly, facilities that are conducive to generation of hydrogen sulphide (H2S) gas (e.g., treatment systems that include use of sulphate reduction) should be approached with caution.

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8.3.4 Data Management and Interpretation

Data management procedures for a project are included in the QAPP and should include standard recordkeeping procedures, document control, and the approach for electronic storage and retrieval. Procedures must ensure data accessibility to users without compromising data security and integrity. The data management system should be capable of integrating various file formats (e.g., photos, drawings, and laboratory data) and information from different disciplines (e.g., hydrology, hydrogeology, and water quality). Use of a database with a GIS interface is recommended.

Ongoing data evaluation is required to assess data quality and provide feedback to environmental management systems. Reasons for ongoing data evaluation include, but are not restricted to the following:

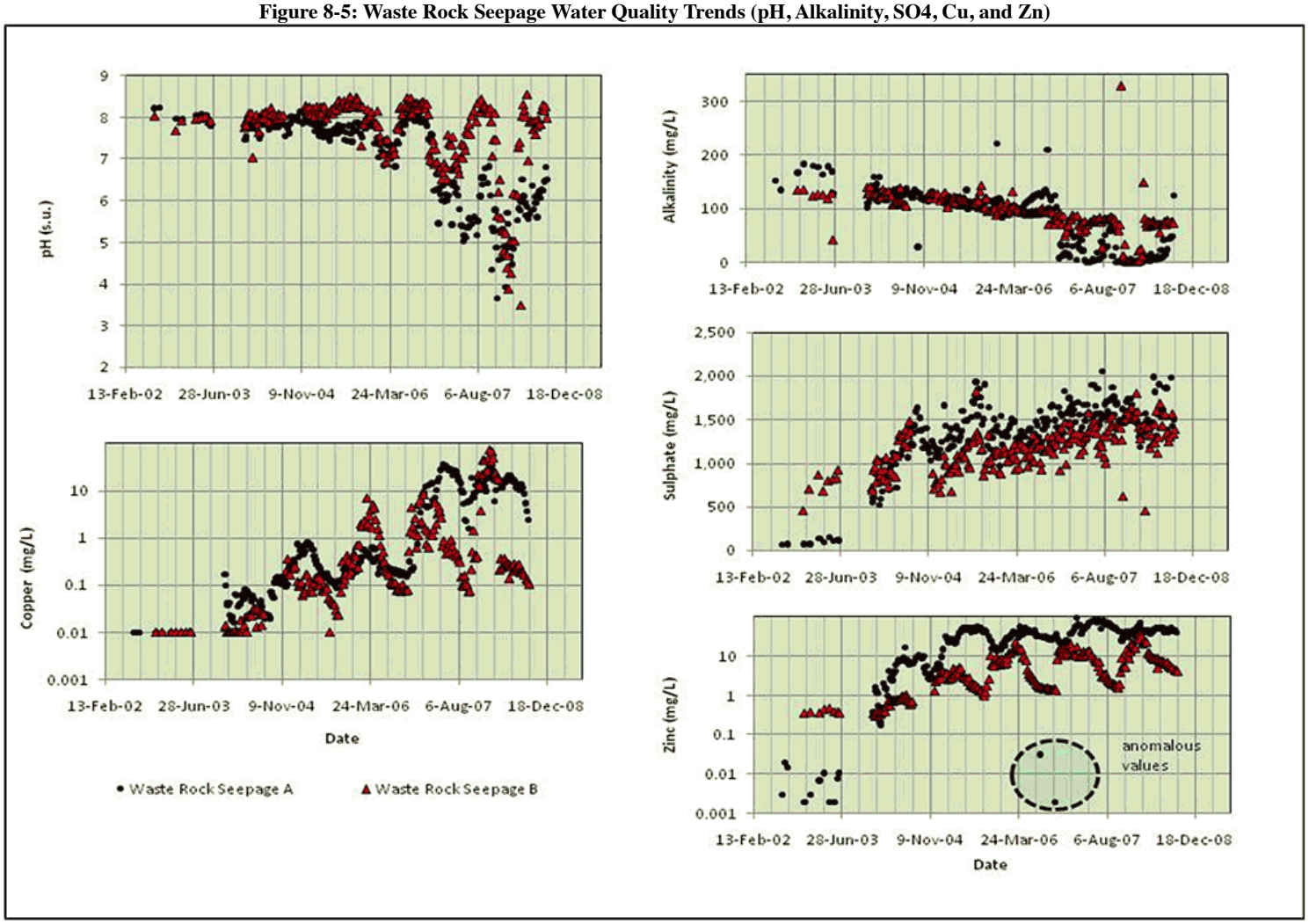
- Statistical analysis to identify changes in environmental conditions (e.g., a change in water or sediment quality) relative to baseline or background conditions

(see Section 8.3.3.2).

- Evaluation of water quality trends to identify the onset of ARD. Graphical tools should be employed to evaluate temporal trends and to ensure early identification of any anomalous results. Frequent assessment and trend analysis of ARD indicator parameters (i.e., pH, SO4, alkalinity, and metals of interest) is required to ensure early identification of the onset of ARD.
- Evaluation of water quality trends to determine the need for additional monitoring locations or increase/decrease in sampling frequency.
- A tiered monitoring approach may be adopted with respect to sampling locations, frequency, or analytes. This approach may include establishing trigger levels for key parameters. If a tiered monitoring approach has been agreed upon, ongoing data management is essential to ensure appropriate implementation of tiering. For example, water quality monitoring may include measurement of indicator parameters (e.g., sulphate, pH, and electrical conductivity) to identify the onset of ARD followed by inclusion of additional metals following establishment of ARD. For parameters with water quality guidelines, a trigger level may be established at a value below the water quality guideline to provide an early warning of possible future exceedances.
- Regular updates to the DSM to assess performance with respect to predictions.

Figure 8-5 shows seepage water quality data from two waste rock dumps over a six-year period. These graphs illustrate the onset of ARD, characterized by declines in pH and increases in metal and sulphate concentrations. Seepage pH remained near neutral for a number of years before acidic conditions were established. The water quality data in Figure 8-5 show that alkalinity, as opposed to pH, may be a better early time indicator of the onset of ARD. At this site, the downward trend in alkalinity is evident before the downward trend in pH. These graphs further demonstrate the importance of frequent monitoring to capture seasonal variability in water quality conditions and the use of graphical techniques to identify anomalous values (see zinc data in Figure 8-5).

Figure 8-5: Waste Rock Seepage Water Quality Trends (pH, Alkalinity, SO4, Cu, and Zn)



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8.3.5 Auditing

ARD monitoring requirements will evolve over a mine's life. Regular review of the monitoring program is required to ensure that objectives are being fulfilled. The components and schedule for program audits are included in the project QAPP. Audits may be performed by internal or external personnel; using both internal and external personnel is desirable. Periodic external audits by third parties allow for a "fresh look" by someone who is removed from day-to-day activities. Evaluation of laboratory performance should be included in audits.

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8.4 Monitoring Program Components

Source and pathway monitoring determines the level of contamination present in the receiving environment. A "contaminant" is defined in this GARD Guide as a substance not normally present (e.g., low pH) or as a substance present above background or reference levels (e.g., a metal or metalloid). To determine whether or not that contamination is capable of causing an effect, the interactions between exposure (from COIs) and effects to receptors of potential concern are evaluated. If effects are shown to occur, or if effects may occur, then a determination must be made as to whether or not those effects could become impacts.

An effect is defined as an alteration to a valued ecosystem component (VEC) that can be positive, negative, or neutral (e.g., Cu and Zn are essential metals that can have positive as well as negative effects on biota, depending on concentration). An impact is an effect that adversely affects the productivity or viability of a VEC community or population of VEC organisms. The possibility of impacts is the primary focus of monitoring, not effects to individual organisms, except in the case of endangered species or humans, where a greater level of protection of individuals may be required.

In terms of ARD, the focus is on the following four primary potential adverse effects, when of sufficient severity, can result in population-level impacts:

- Lowered pH
- Increased sulphate ion concentrations
- Increased concentrations of bioavailable metals and metalloids
- Precipitation of metal hydroxides (reduced habitat and oxygen supply)

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8.4.1 Acid Rock Drainage Sources

The primary focus of ARD source monitoring is typically to provide an early warning of ARD release. In Sections 8.4.1.1 through 8.4.1.3 a number of individual potential sources for ARD and specific monitoring requirements are described.

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8.4.1.1 Mine Workings

Sulphide minerals exposed to the atmosphere in underground workings and open pits are a potential source of ARD. During operations, dewatering programs (removal of groundwater with wells and sumps) minimize groundwater interaction. When mining ceases, flooding of mine workings may flush stored oxidation products from pit and mine walls. Backfill materials (e.g., waste rock and tailings) may also contribute metals and acidity to a mine pool or pit lake.

Hydrogeologic site conditions must be considered in the development of a monitoring program for underground workings. Below-drainage (i.e., fully flooded) mines tend to have a finite life for acid mine drainage discharge whereas acid mine drainage from above-drainage (partially flooded mines) may persist for decades, or longer, depending upon the exposure and reactivity of acid generating walls (Demchak et al., 2004). Peak contaminant concentrations generally occur during the first flush because of the rinsing of accumulated sulphide oxidation products. During water table rebound, underground workings may transition from a groundwater sink to a groundwater source.

An understanding of the pit lake water balance is required to determine if a pit lake will form and if the pit will be a hydrologic source or sink.

Water Quality Monitoring – During operations, collection of sump and dewatering well samples provides a direct assessment of ARD. During pit flooding, collection of samples from the mine pool, surface expressions, and within the pit lake provides source characterization.

A chemocline or thermocline may develop in open pits and underground workings. Collection of water quality samples to assess the presence of a chemocline and evaluate changes in chemistry with depth may be appropriate.

Hydrologic Monitoring – During operations, dewatering volumes and information to estimate the size of the void created by mining (i.e., volume of material removed) should be recorded. This information is used to estimate time to water table rebound following cessation of dewatering activities. During water table rebound, water levels within the pit, underground workings, or dewatering wells are monitored to evaluate the rate of water-table rebound. This water-level information is required to estimate the timing and location of possible discharges to the environment (e.g., water discharge from underground adits or shafts or discharge from a pit lake).

ARD Process Monitoring – Wall washing tests may be conducted to provide data on sulphide oxidation rates and metal leaching from mine and pit walls (Photo 8-1) (Price, 1997).

Photo 8-1: Collection of a Wall Washing Sample from a Pit Face

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8.4.1.2 Waste Rock Piles

Waste rock piles are typically described as heterogeneous, consisting of a mixture of rock types with variable ARD potential and a range of particle sizes. In some cases, operational characterization (e.g., total sulphur and NP analysis) of waste rock may be conducted to segregate waste rock on the basis of ARD potential. Precipitation is the primary water source moving through this waste. Typical components of a waste rock monitoring program are listed in Table 8-6.

Table 8-6: Components of Waste Rock Pile Monitoring Program

Objective	Data Collection	Method/Instrument	Reference
ARD/ML leaching - water quality	Pore water - unsaturated Zone	Pressure-vacuum (suction) lysimeters	
	Pore water - saturated zone	Piezometers/wells	
	Runoff	Weirs	
	Seepage	Weirs/wells	
Water flow	Precipitation	Rain gauge	
	Infiltration rate	Gravity lysimeter	(ACMER, 2000) Method P-001
	Water permeability	Infiltration/slug tests	
	Moisture content	Neutron probe	
		Time-domain Reflectrometry (TDR)	
	Matric suction	Tensiometer	
		Thermal conductivity Sensor	
	Soil-water characteristic curve	Laboratory test	
	Unsaturated (saturated) Hydraulic conductivity	Laboratory test	
ARD/ML process	Temperature (profile)	Thermistor strings	(ACMER, 2000) Method P-002 (probe installation) and P-003
	Oxygen (profile)	Well gas ports	(ACMER, 2000) P-006
	Air Permeability	Porosity	(MEND, 1993)
	Oxygen Diffusion	Well gas ports	(MEND, 1993)
	Particle size distribution	Sieve analysis	

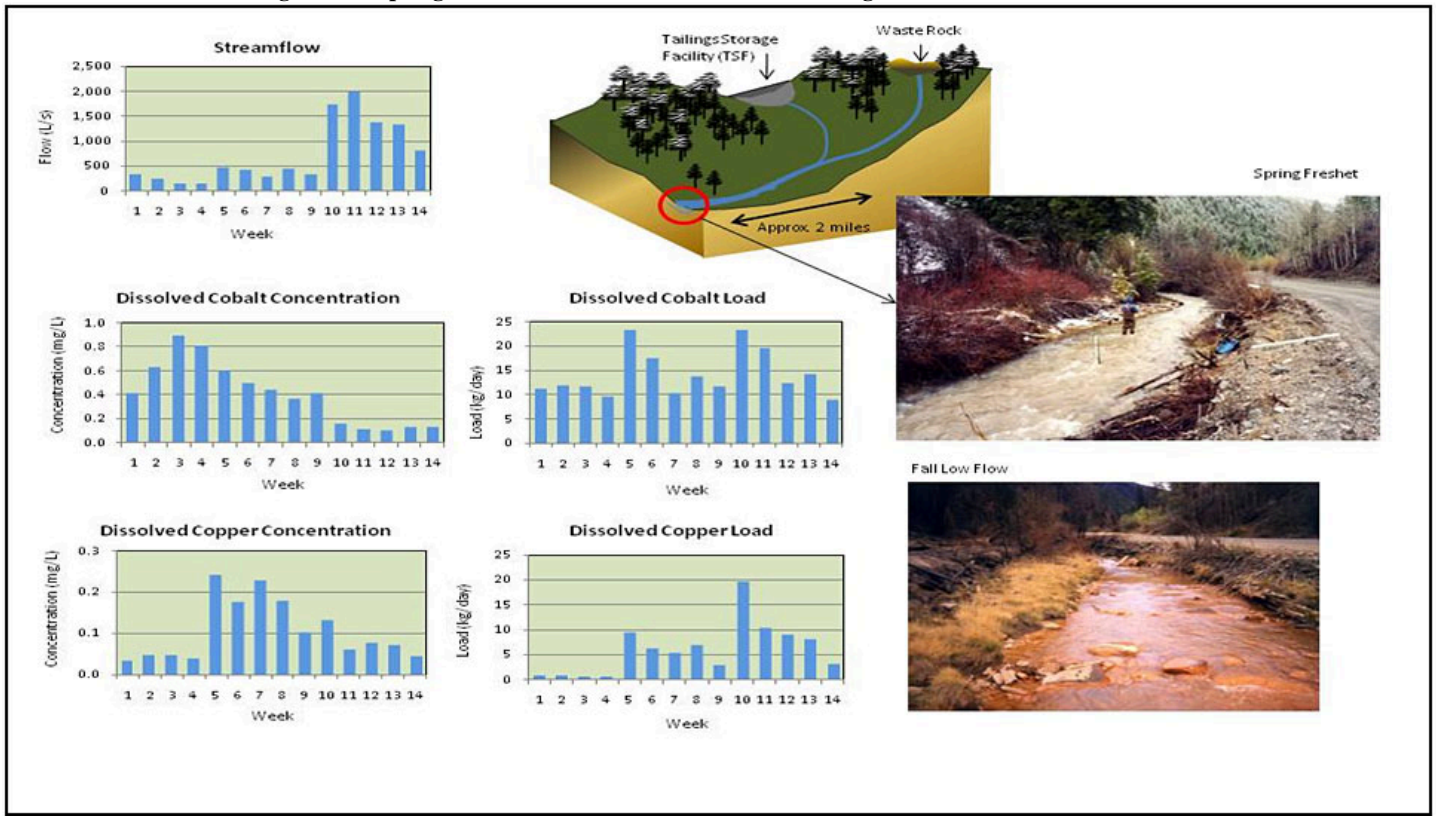
Water Quality Monitoring - Collection and analysis of water samples provides a direct assessment of the onset or magnitude of ARD within a waste rock facility. Collection of water samples may include seepage (typically collected at the toe of the pile), runoff, and pore water from within the pile. Pore water samples are collected using lysimeters or piezometers from the unsaturated and saturated portions of the pile, respectively. Lysimeters may also be used to measure water volumes to calculate infiltration rates (Photo 8-2). A seasonally stratified sampling program is appropriate for collection of water samples.

Photo 8-2: Waste Rock Lysimeter in an Arid Climate

Hydrologic Monitoring – The range of particle sizes in a waste rock pile complicates measurement or estimation of infiltration. Water infiltration through waste rock is a combination of matrix flow and preferential flow. Best practices for instrumentation of waste rock piles to quantify key infiltration processes are still in development; however, the parameters of most interest in characterization of hydrogeologic conditions are moisture content, matric suction, soil-water characteristic curves, and unsaturated hydraulic conductivity (Smith and Beckie, 2003). Infiltration is measured directly through installation of lysimeters within the pile.

ARD Process Monitoring - Waste rock monitoring may also include collection of data to evaluate the rate or status of ARD for predictive evaluations. The availability and transport of oxygen to reactive sulphides controls the rate of sulphide oxidation. Therefore, prediction of the rate of sulphide oxidation within a waste rock stockpile requires an understanding of gas transfer mechanisms within the pile (i.e., diffusion and advection) (see Chapter 2 for more detail on the ARD process). To define gas transfer, the following bulk physical parameters must be measured: thermal conductivity, gas diffusion coefficient, and gas permeability. MEND (1993) and ACMER (2000) provide information on field procedures for instrumentation and collection of data to evaluate gas transfer Table 8-6.

Figure 8-6: Spring Thaw Stream Concentration and Loading Trends (March 23 to June 22)



Pyrite oxidation is an exothermic reaction that consumes oxygen. Measurements of temperature and oxygen profiles within a waste rock pile provide an indirect means to assess the rate of sulphide oxidation within a waste rock facility after ARD is well established. This method is applicable provided the pile does not contain other oxidizable material (e.g., carbonaceous material).

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8.4.1.3 Tailings Storage Facility

Tailings are discharged to storage facilities by three methods: subaerial slurry, subaqueous, or dry deposition. Compared to waste rock, tailings are homogenous with a more consistent distribution of acid generating and acid neutralizing materials; however, if associated with a particular size fraction, segregation may occur during deposition. The fine particle size of tailings results in low permeability to oxygen and water.

Spatial differences in sulphide reactivity and pore water quality must be considered in the design of a TSF monitoring program. Tailings moisture content is a primary control on the rate of oxygen diffusion into tailings and therefore the rate of sulphide oxidation. Sulphide oxidation is typically restricted to the uppermost tailings exposed to the atmosphere. Shallow acidic pore water may be neutralized as it migrates downward through the tailings. Tailings pore water quality is therefore typically highly variable with depth. The time for acidic seepage to emanate from the base of sulphide tailings will be a function of both the reactivity of the tailings (i.e., the relative rates and amount of acid generation by sulphide oxidation and acid neutralization by dissolution of minerals with buffering capacity) and the travel time through the tailings. The duration of effects from sulphide oxidation from tailings can range from decades (e.g., tailings with a low sulphide content and shallow water table in the tailings) to centuries (e.g., tailings with a high sulphide content and deep water table) (Blowes et al., 2003). Typical components of a tailings monitoring program are listed in Table 8-7.

Table 8-7: Components of Tailings Storage Facility Monitoring Program

Objective	Data Collection	Method/Instrument
ARD/ML leaching water quality	Pore water- unsaturated zone	Core sample extraction (e.g., centrifugation, pressurised consolidation – squeezing, pore

		water displacement)
	Pore water – saturated zone	Suction lysimeters
	Runoff	Weirs
	Seepage	Weirs/wells
	Water cover (subaqueous disposal)	
Water flow	Hydraulic conductivity	Estimated from grain size, slug tests or pumping tests
	Hydraulic head	Water level measurement in piezometers/wells pond elevation (subaqueous disposal)
	Air permeability	Porosity
ARD/ML process	Moisture content	Neutron probe
	Pore gas O2	Well gas ports
Time domain reflectrometry (TDR)		

Water Quality Monitoring - Collection and analysis of water samples provides a direct assessment of the onset or magnitude of ARD within the tailings. Collection of water samples from a tailings impoundment may include (sample types may not be applicable to all TSF designs) tailings slurry water from the point of discharge, tailings pore water, tailings pond supernatant (subaqueous disposal), tailings seepage (embankment or from collection drains), and tailings runoff.

Different methods may be used to collect tailings pore water from the unsaturated and saturated zones (Table 8-7). Collection of pore water samples with depth allows evaluation of current conditions and also allows the progression of acidification fronts through the tailings. Differences in geochemical conditions at depth may result in enhanced mobility of some constituents (e.g., reductive dissolution resulting in arsenic release). Therefore, water quality results from shallow pore water or tailings pond supernatant may not identify all COIs. Collection of tailings pond supernatant should also consider the potential for vertical stratification.

Determination of the analyte list should consider inclusion of beneficiation process chemicals (e.g., cyanide). If the TSF is used for codisposal of other waste materials, inclusion of additional analytes may be appropriate.

During operations, milling processes can produce thiosalts, especially from pyrrhotite ores. These thiosalts usually report to tailings and can be the source of additional concerns related to the further oxidation to sulphate, which both lowers the pH and consumes oxygen. Tailings from these reactive ores should be monitored for thiosalt presence and for the associated oxidation of these thiosalts and its potential effect on tailings water quality and the environment (see Chapter 2 for additional information on thiosalts).

In the case of subaqueous disposal in a lake or the marine environment, additional monitoring requirements are related to sediment quality and smothering of sediments and the potential for lateral and vertical distribution (i.e., upwelling) of tailing-related water.

Hydrogeologic Monitoring - The hydrogeologic conditions within a TSF are controlled by tailings grain size and depositional history. Measurements of hydraulic head and hydraulic conductivity can be used to estimate the rate of water movement through the tailings. Geochemical characteristics of the pore water may also serve as tracers to estimate the rate of water movement (Blowes et al., 2003).

ARD Process Monitoring – Tailings solids sampling and analysis may be conducted during operations to characterize changes in the waste composition and acid base accounting. Data collection to support predictive sulphide oxidation modeling and verification and for performance monitoring of mitigation measures (e.g., covers) may include moisture content profiles, porosity, and pore gas oxygen concentrations.

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8.4.2 Pathways

The goals of pathway monitoring may include characterization of current conditions, assessment of fate and transport of COIs, and estimation of contaminant loading. Surface water and groundwater are the primary pathways of interest for impacts from ARD sources.

Mine discharges may include both controlled releases of effluent (e.g., water treatment plant effluent discharge) and more diffuse releases (runoff and seepage from waste facilities). ARD discharge occurs within the mine property boundary where initial mixing with surface water or groundwater occurs. The COI may eventually migrate to the property or compliance boundary and beyond.

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8.4.2.1 Surface Water (Streams and Sediment)

Water Quality – BACI (see Table 8-4) is the preferred monitoring location design for stream water quality monitoring. Exposure stations should be sited near ARD sources or effluent discharges where complete mixing is achieved. Collection of multiple samples along the width of the stream will allow for an assessment of within-station variance and the degree of mixing. Evaluation of the transport of COIs downstream of a source requires collection of samples upstream and downstream of surface water inflows.

Flow-stratified sampling is often appropriate. Figure 8-6 shows stream flow and concentration trends (dissolved copper and cobalt) downstream of multiple ARD sources (TSF and waste rock). These data illustrate that concentration trends for parameters may differ, resulting from differences in both source release and transport within the receiving environment (i.e., differing degrees of attenuation).

Collection of samples can be conducted manually or with automatic programmable samplers. Manual collection allows immediate determination of field parameters and submission of samples for analysis. Programmable samplers allow collection of multiple samples over time and can be used to capture unpredictable events (e.g., storm flush). The potential for damage to the automatic sampler during flood events should be considered when siting the equipment. The effects of a delay between sample collection and analysis are a potential disadvantage of automated samplers. Collection of grab samples is appropriate for fully mixed systems. Composite samples (e.g., flow weighted) can be collected if complete mixing has not been achieved.

Diel (24-hour) sampling may be required to characterize within-station variance for some parameters. Dissolved concentrations of some trace metals exhibit consistent and substantial diel variations, particularly in streams with neutral to alkaline pH values. Daily changes in water temperature and pH and their effect on metal sorption are the most likely cause of observed diurnal metal cycles. Metal concentrations typically show increasing trends during the night and decreasing trends during the day (e.g., Cd, Mn, and Zn), primarily related to changes in water pH related to respiration vs. photosynthesis of aquatic plants. However, the opposite trends have been observed for arsenic (USGS, 2003). In the case of ARD, such behaviour is generally not observed due to the acidic nature of the solution and the relatively minor changes relative to the overall metals load.

Flow – Measurements of stream discharge are required to calculate chemical loading, and such measurements should be conducted concurrent with water quality sampling. Instantaneous stream discharge measurements are made by dividing the width of a stream into sections and measuring the cross sectional area and average water velocity using a current velocity meter (Photo 8-3). Total river discharge is estimated by summing the discharge within each subsection where the discharge within each subsection is the product of the subsection width, midpoint depth, and average velocity. A stage-discharge relationship (curve) can be developed to convert water level measurements (from a gauge or transducer) to streamflow. Approximately 10 stage/discharge measurements, taken over a range of flows, are typically required to establish a stage-discharge curve (MEND, 2001). Characterization of high flows to capture the high end of the stage-discharge curve may require sampling during precipitation events. Safety aspects associated with sampling during high-precipitation events should be taken into account. Streamflow monitoring locations should be sited in areas with the following characteristics: relatively straight channel, uniform bed elevation, nonturbulent flow, and close proximity to staff gauge/transducer.

Photo 8-3: Stream Discharge Monitoring Using a Current Meter

The accuracy of discharge measurements in mountain streams using traditional methods (e.g., weir or current velocity meter) is reduced because of the exclusion of the contribution from the hyporheic zone (subsurface volume of sediment and porous space adjacent to a stream through which stream water readily exchanges). The hydrology of mountain streams is complex. Variability in streambed topography, resulting in variation in stream water slope, influences the potential energy distribution at the boundary between the stream and subsurface. Changes in pressure distributions on the channel bed cause surface water to flow into and out of the bed. Individual flowpaths of exchange can range in scale from centimeters to tens to hundreds of meters with travel times from minutes to years (Harvey et al., 1996). Tracer tests have been used to estimate the following hydrologic properties in mountain streams: velocity, travel time, groundwater inflow, and mixing of solutes (USGS, 1997). Selection of a conservative tracer is key to the success of tracer dilution tests. Guidance for the design of stream discharge tracer studies is presented in Kilpatrick and Cobb (1985).

Weirs, either as temporary or permanent installations, are also used to estimate streamflow. A weir is an overflow structure built perpendicular to an open channel axis to measure the rate of the flow of water. When properly constructed and operated, flow is estimated by measuring the head of water above the crest of the weir. The shape of the crest overflow governs the relationship between head measurement and discharge. Common weir types include rectangular, V-notch, and Cipoletti (trapezoidal) weirs. Guidelines for the appropriate use of weirs and their maintenance are provided in the Water Management Manual (U.S. Department of the Interior – Bureau of Reclamation, 2001).

Accurate flow measurements are essential to evaluating chemical loading. Measurement of electrical conductivity, in association with flow measurements, may allow for identification of anomalous flow measurements (Wolkersdorfer, 2008).

Sediment – Because of the tendency for sediment to act as a metal sink, and conversely a source of metal release and toxicity to aquatic life, river and lake sediment monitoring is often a component of impact assessment. Sampling locations should target fine-grained depositional zones. The vertical accumulation of COIs is affected by bioturbation, bioirrigation, sedimentation rates, and turnover events. Recommended depths of sample collection are

variable; however, typically samples are collected up to a depth of approximately 10 to 15 centimeters to encompass the zone within which most burrowing animals live. Consistency in sample collection depth between events is critical for meaningful comparisons of temporal data. Grab or core sampling methods can be used; core sampling provides greater precision for sample depth. Sample collection should avoid periods of disturbance (i.e., high flows or seasonal turnover events). Sample analysis typically includes chemical analysis (metals and sulphides; sulphides are particularly important with respect to possible sediment toxicity testing), grain size, total organic carbon, and wet/dry weight. Sequential extraction or acid volatile sulphide (AVS) analyses may be performed if information on metal phases is required for toxicity or bioavailability assessments. The grain size fraction used for chemical analysis must be defined.

Collection of pore water samples is less common, but may be required for detailed toxicity studies. In situ sampling methods (e.g., suction or dialysis samples) provide better representation of the anoxic conditions typically present than do laboratory methods such as centrifugation (Chapman et al., 2002).

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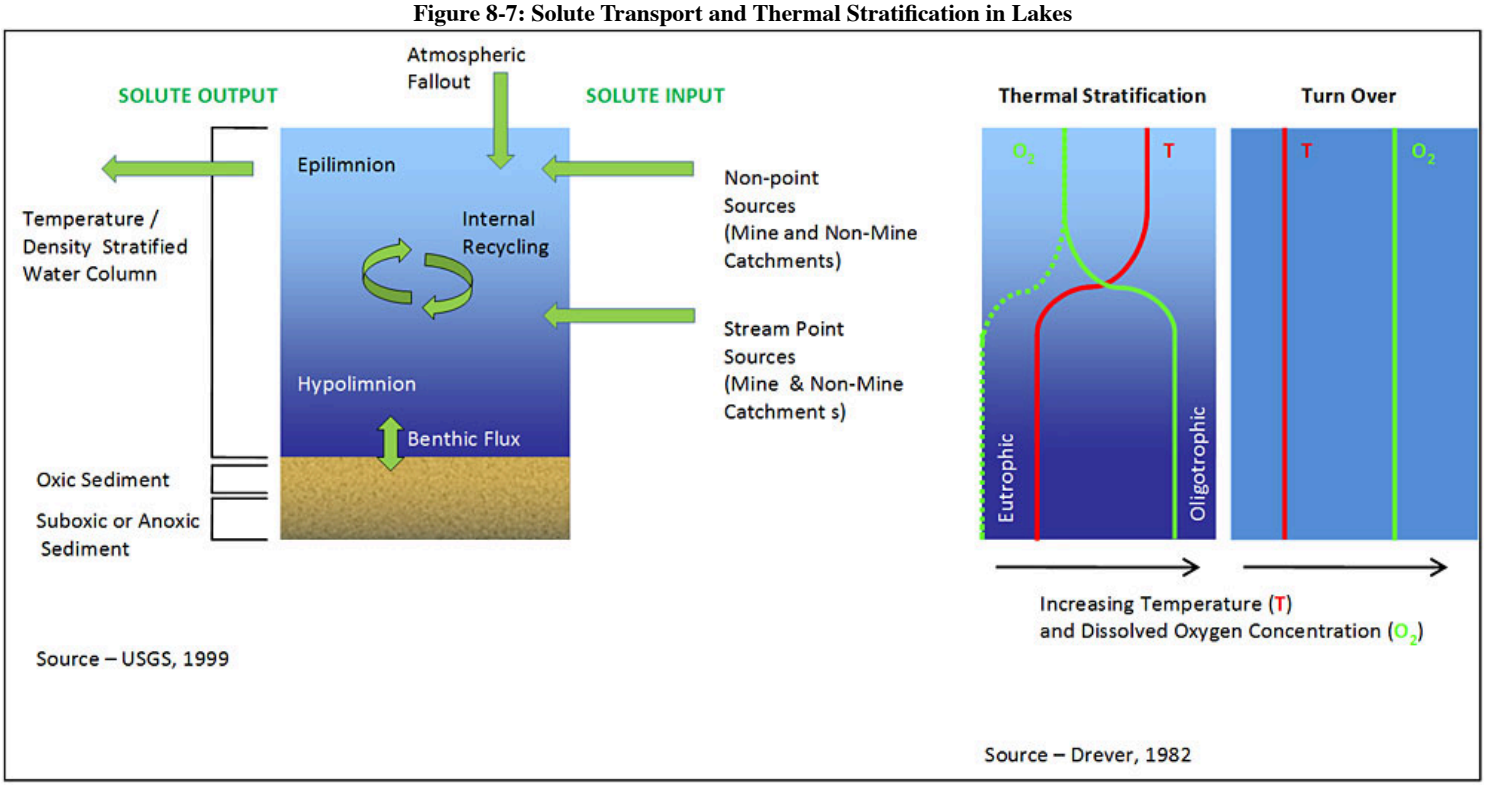
8.4.2.2 Lake Monitoring

Monitoring design to assess impacts to lakes must consider the following characteristics that affect water quality and constituent fate and transport (Hem, 1992).

Figure 8-7: Solute Transport and Thermal Stratification in Lakes



- Retention Time – In comparison to streams, the longer retention time in a lake provides more time for kinetically slow reactions to come closer to completion.
- Degree of Mixing – Incomplete mixing in a lake may result in significant spatial variability in water quality.
- Evaporation – In closed basin lakes, constituent concentrations will increase due to evaporation.
- Thermal Stratification – Heating of the upper water layer during warm periods results in stratification because of the relationship between water density and temperature. Thermal stratification separates warm lighter surface water (epilimnion) from cold heavier bottom water (hypolimnion). Minimal solute exchange between the layers may result in thermal and chemical stratification and the development of a thermocline/chemocline. Stratification can also cause oxygen depletion at depth because of atmospheric isolation and oxygen consumption by biochemical processes. A change to cooler temperatures may result in lake turnover (mixing) and a change to more uniform water quality conditions, including more uniform dissolved oxygen concentrations.

The physical, chemical, and biological conditions within a lake will affect the transfer of metals between the water and sediment phases. If the CSM identifies metal loading to lake bed sediments as a concern, identification of the primary mechanisms responsible for metal transfer between the aqueous phase (water column or sediment pore water) and solid phase (sediments) within the lake and the geochemical conditions driving these reactions may require collection of specific data.

Lake monitoring may include the collection of water quality samples. The degree of mixing within a lake will dictate requirements for spatial collection of samples. Collection of depth profiles of key parameters (e.g., temperature, dissolved oxygen, electrical conductivity) will provide information on the degree of stratification and the need for collection of depth stratified samples.

Evaluation of temporal water quality trends necessitates collection of proper baseline data or monitoring of reference lakes, or both. Without appropriate reference (and background) measurements, water quality changes due to other factors (acid rain, climate change) may be incorrectly attributed to mine operations. Monitoring of background drainages outside of the mine catchment may be required to evaluate other sources of loadings. Temporal comparisons of lake water quality should be made with samples taken during the same season. To assess metal loadings to a lake, data collection to calculate a loading budget may be more appropriate than in-lake water quality measurements. Measurement of inflow and outflow water quality and flow allows for determination of the lake as a constituent source or sink. Data indicative of accumulation of a COI within the lake could trigger collection of data on likely sinks (sediment and aquatic organisms).

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8.4.2.3 Marine Monitoring

For coastal sites, marine monitoring may be required if the CSM indicates a potential for ARD release to this environment. The physical (e.g., tidal and ocean currents) and chemical (e.g., high ionic strength, chemical gradients) dynamics of the marine system result in very site-specific approaches to monitoring. Biological monitoring may be the most efficient way to evaluate ARD impacts (MEND, 1990). For submarine tailings disposal, monitoring to evaluate the spatial extents of dispersion of the tailings plume is often required.

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8.4.2.4 Groundwater

BACI (see Table 8-4) is the preferred monitoring location design for groundwater monitoring. Information on the site geology, topography, and hydrology (including wetlands) should be reviewed to develop a conceptual model of groundwater flow directions before siting monitoring wells. Land surface topography is used to assess the general direction of groundwater flow and identify areas of groundwater recharge and discharge. Topographical highs are recharge areas where groundwater flow is directed downward. Groundwater discharges at topographical low areas to springs, lakes, wetlands, or streams.

The monitoring well network is designed to provide information on groundwater quality and groundwater flow (direction and velocity). Siting of monitoring wells should consider the following:

- Groundwater Flow – A minimum of three groundwater level measurements from the same aquifer are required to determine groundwater flow direction. Calculation of groundwater velocity requires information on the hydraulic gradient (calculated from water-level measurements) and the hydraulic properties of the aquifer (porosity and hydraulic conductivity [K]). Hydraulic conductivity can be estimated using a variety of laboratory or field testing methods (e.g., estimated from grain size, laboratory falling-head permeameter tests, slug testing, and pump testing). Tracer studies can also be used to characterize groundwater flow. Numerical models may be used as a tool in the evaluation of groundwater flow.
- Impact Well Siting – Wells sited to assess impacts to groundwater quality from a source must consider groundwater flow directions and velocity. Wells sited to provide an early warning of impacts should not be placed too far downgradient or at too great a depth (Richards et al., 2006). Spatial monitoring well coverage must consider all three dimensions. The potential for mining activities to change groundwater flow patterns or water-table depth should also be evaluated to determine well screen elevations (e.g., dewatering wells, ponded water conditions in a TSF).
- Groundwater Quality – Fate and Transport – Characterization of aquifer solids (e.g., neutralization potential, cation exchange capacity) may provide useful data for groundwater fate and transport assessments, specifically in the evaluation of metals attenuation or acidity neutralization. The sequence of pH buffering reactions that occur during migration of an acidic plume is well documented in areas affected by mining activity and described in Blowes and Ptacek (1994), Stollenwerk (1994), and Brown et al. (1999).
- Geophysical Methods may also be used to assess the migration of an ARD plume and may be used as a tool in siting wells at sites where ARD contamination exists (MEND, 2001).
- Springs – Baseline characterization of site hydrogeology should include a survey of seeps and springs. Collection of water quality and flow measurements may be included in baseline and operational monitoring.
- Monitoring Frequency - A fixed frequency sampling program is typically employed for groundwater monitoring (e.g., monthly groundwater level measurements and quarterly groundwater quality sampling). Continuous water-level measurement using transducers may be appropriate (e.g., monitoring of groundwater level decline associated with dewatering operations).
- Well Construction – Use of acid or sulphate resistant materials in the construction of ARD monitoring wells may be appropriate (e.g., use of PVC or stainless steel screens instead of a mild steel or use of sulphate resistant grout).

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8.4.2.5 Groundwater/Surface Water Interactions

Investigative monitoring may be required to identify groundwater discharge of COIs to surface water. Synoptic sampling involves collection of samples from multiple locations during a short period of time to provide a “snapshot” of conditions and identify sources and sinks to the water resource of interest. Synoptic stream sampling involves collection of surface water quality samples and flow measurements along a flow path synchronous with flow velocity to track loading and identify sources and sinks. This technique is often used to identify groundwater COI sources.

Following identification of areas of groundwater seepage, seepage meters can be used to calculate seepage rates or collect seepage samples for chemical analysis. The basic concept of the seepage meter is to cover and isolate part of the sediment-water interface with a chamber open at the base and to measure the change in the volume of water contained in a bag attached to the chamber over a measured time interval.

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8.4.2.6 Climate

Collection of site climatological data is important to develop site-wide water balance. Installation of precipitation gauges to collect daily rainfall data and evaporation pans provide data for calculation of net infiltration. Wind speed, wind direction, relative humidity, and temperature data may also be compiled if a comprehensive evaluation of site specific conditions is required. In cold climates, snowpack may be measured to evaluate hydrologic conditions during spring thaw.

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8.4.3 Mitigation Measures

The following are examples of typical monitoring requirements for evaluation of the effectiveness of engineering controls designed to control or mitigate ARD releases:

- Water Treatment (Passive and Active) – Water-quality monitoring of treatment influent and effluent samples is standard practice. Passive treatment systems may require more frequent monitoring during certain climatic conditions to ensure consistent performance (e.g., periods of high flow or extreme ambient temperatures).
- Cover Performance – Cover designs to prevent or reduce sulphide oxidation are designed to limit oxygen transfer or water infiltration into a waste material. Monitoring designs to evaluate the effectiveness of cover performance are the same as those employed to evaluate ARD processes within a waste material and are described in Section 8.4.1.
- Liner Performance – Waste facilities may be lined to prevent migration of seepage into groundwater. Groundwater monitoring wells may be sited adjacent to waste facilities to provide early warning of COI release because of liner failure.

The mitigation measures implemented at a particular site will dictate the monitoring required to evaluate performance. Additional information mitigation measures monitoring is provided in Chapter 6.

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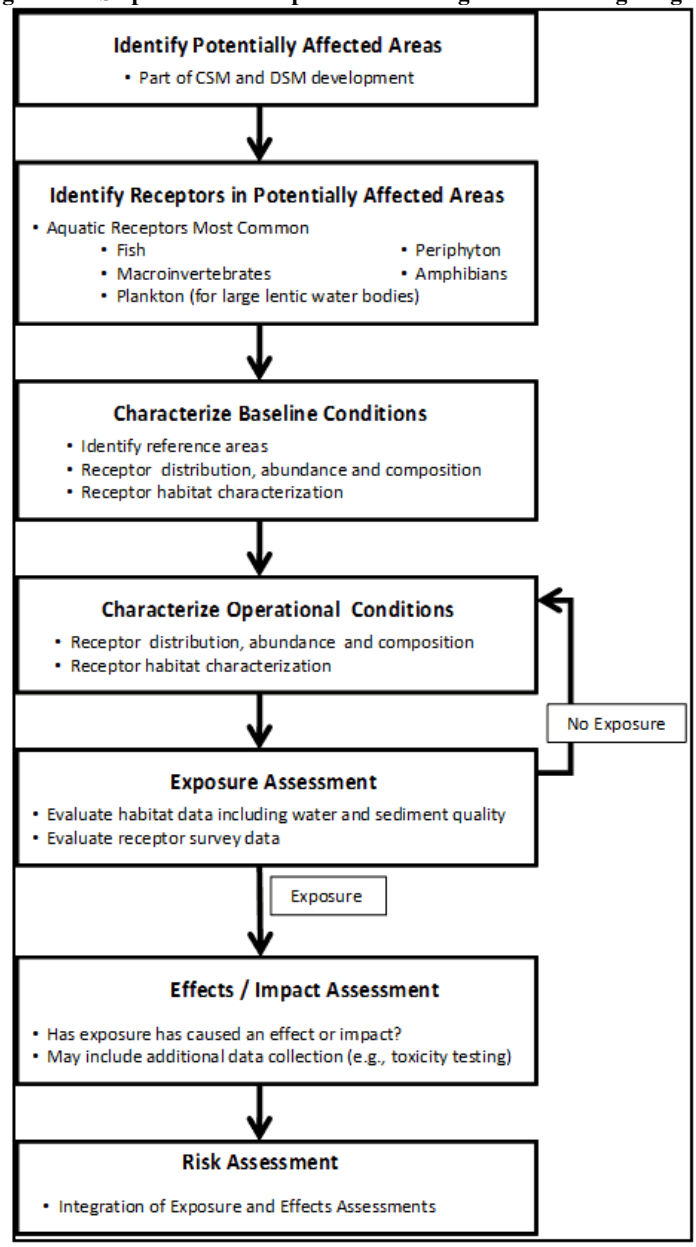
8.4.4 Receptors

Receptor monitoring is conducted to identify any changes in biota attributable to mining. Metal or acidity release to the receiving environment may alter population dynamics or alter the community composition of an ecosystem. Receptor monitoring is designed to detect changes in species composition (the presence or absence of taxa within an area), abundance or distribution of plants and animals, or both. Unlike water quality monitoring, which provides information on environmental conditions at a point in time, biological monitoring provides an indication of environmental conditions over time.

Figure 8-8 shows the steps in the development of a biological monitoring program. At the start of a biological monitoring program, receptors in potentially affected areas are identified. Selection of receptors for inclusion in the monitoring program considers the following: predicted COIs, range of biota exposed, toxicological implications of exposure to specific biota, and potential for recovery following mitigation (e.g., recolonization, reproductive potential).

Figure 8-8: Steps in the Development of a Biological Monitoring Program


Identify Potentially Affected Areas
• Part of CSM and DSM development
Identify Receptors in Potentially Affected Areas
• Aquatic Receptors Most Common
• Fish
• Macroinvertebrates
• Plankton (for large lentic water bodies)
• Periphyton
• Amphibians
Characterize Baseline Conditions
• Identify reference areas
• Receptor distribution, abundance and composition
• Receptor habitat characterization
Characterize Operational Conditions
• Receptor distribution, abundance and composition
• Receptor habitat characterization
No Exposure
Exposure Assessment
• Evaluate habitat data including water and sediment quality
• Evaluate receptor survey data
Exposure
Effects / Impact Assessment
• Has exposure has caused an effect or impact?
• May include additional data collection (e.g., toxicity testing)
Risk Assessment
• Integration of Exposure and Effects Assessments

Assessment and measurement endpoints are defined for each biological receptor. An assessment endpoint is the explicit expression of the environmental value that is to be protected (e.g., survival, growth, and reproduction of major aquatic communities). A measurement endpoint is the measurable ecological characteristic that is related to the assessment endpoint (e.g., actual determinations of survival, growth, and reproduction using laboratory or other tests or field observations, or both).

Fish and benthic macroinvertebrates are often selected to measure effects from ARD (Photo 8-4, Photo 8-5, and Photo 8-6). Fish are selected for monitoring because of their economic value, public perception (impacts are often visible and well understood by the public), and their use as an indicator of possible impacts to lower trophic levels. Reduced pH or trace metals can affect behavioural, respiratory, and other physiological fish functions. Fish population characteristics (e.g., length and weight relationships, age structure, sex ratio, fecundity, and growth) and tissue metal concentrations are common metrics (MEND, 2001).

Photo 8-4: Benthic Macroinvertebrate

Photo 8-5: Benthic Macroinvertebrate Sampling with a Hess Sampler

Photo 8-6: Fish Survey Using Nets

Benthic macroinvertebrates are small animals without backbones that inhabit bottom substrates and are retained by mesh sizes ≥ 200 to 500 micrometers (μm). Benthic assemblages are comprised of a range of organisms that exhibit variability in their tolerance to impacts (e.g., sedimentation and metals)

(USEPA, 2003). Reduced density, reduced taxa richness, or a shift from sensitive to tolerant benthic taxa are all indicators of impacts. Reasons to include benthic macroinvertebrates in monitoring programs include their sessile nature, their use as indicators of water quality and habitat conditions, and they are a food source for fish, an indirect measure of ARD impacts to fish populations.

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8.4.4.1 Establishment of Baseline Conditions

The CSM identifies areas that may be affected by ARD release. Monitoring is conducted to establish baseline ecological conditions within these areas at both reference and exposure stations. Reference and exposure aquatic monitoring stations should be sited in areas with similar physical and ecological characteristics to minimize the potential for differences because of natural confounding factors (e.g., current velocity, depth, substrate, dissolved oxygen). The first aquatic monitoring station should be located within the mixing zone near the point of ARD release. Additional downstream stations are sited at increasing fixed intervals. The final monitoring location should be beyond the point of potential environmental impacts. Co-location of water quality and sediment sampling stations may be appropriate.

Habitat, a consideration in the selection of sampling locations, should be characterized at all locations. Information requirements for aquatic habitats are shown in Table 8-8 (USEPA, 2003). Determination of relevant information will be receptor dependent.

Table 8-8: Aquatic Habitat Information Requirements for Biological Monitoring

Habitat	Information
Stream	Gradient, width and depth, pool frequency, substrate composition, streambank erosion, flow characteristics, temperature, and dissolved oxygen
Lake or reservoir	Depth, surface area, littoral zone area, aquatic vegetation, and substrate composition
Riparian zone	Width, percent cover and composition of vegetation by strata, and estimated shaded area by season

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8.4.4.2 Sample Collection

Site conditions, receptors of potential concern, and assessment endpoints will dictate sample collection protocols. General guidelines for benthic macroinvertebrate and fish monitoring include MEND (1997), Environment Canada (2002), and USEPA (2003).

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8.4.4.3 Data Evaluation - Exposure Assessment

Habitat (including water and sediment quality) and biological monitoring data are evaluated to determine if receptors have been exposed to COIs. The exposure assessment attempts to answer the following questions:

- Are COIs elevated?
- Could biomagnification occur? Biomagnification is only relevant for a very few organic substances (e.g., the organic form of mercury - methyl mercury), but not for inorganic metals or metalloids.
- How does environmental fate of a COI affect receptor exposure?

Confirmation of exposure triggers an effects assessment.

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8.4.4.4 Data Evaluation - Effects Assessment

The effects assessment attempts to answer the following questions:

- Are COIs biologically available? The bioavailability, bioaccessibility, and bioreactivity of the COI are determined. Bioavailability can be estimated for metals by modelling (e.g., the Biotic Ligand Model [BLM]) (Paquin et al., 2000) or laboratory testing.
- Are COIs toxic? The magnitude of any toxicity associated with exposure to COIs is assessed. Such information is typically determined from toxicity tests with well-established standard test organisms.
- Are resident communities altered? Alteration of resident community structure is assessed by identifying and enumerating assemblages, and using both univariate and multivariate analyses to determine similarities and differences from reference areas and baseline conditions.
- Are COIs causative? Investigation of causation involves additional or more extensive studies as appropriate to site-specific circumstances (e.g., spiked toxicity tests, toxicity identification evaluation [TIE], contaminant body residue [CBR] analyses, tests with resident organisms, and in situ bioassays).

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8.4.4.5 Risk Characterization

Combining exposure and effects assessments differentiates contamination from pollution ("pollution" is defined here as contamination that results in adverse biological effects). Including both toxicity testing and assessment of any alterations to resident communities differentiates effects from impacts. Exposure and effects assessments are integrated to determine whether or not significant effects are occurring or are likely to occur. In addition, the nature, magnitude, and areal extent of effects on the selected assessment points are described. The COIs that may be causing or substantially contributing to such effects are identified to the extent possible.

The results for each line of evidence are compiled and interpreted separately. Subsequently, they are combined and integrated, including uncertainty and best professional judgment, to establish a weight of evidence for assessing risks. Risks of adverse effects can generally be considered in the following four categories:

- Negligible – similar to those for baseline or reference conditions, or both
- Moderate – minor or potential differences compared to baseline or reference conditions, or both
- High – major or significant differences compared to baseline or reference conditions, or both
- Uncertain – requiring further study (determined on a case- and site-specific basis)

The latter two categories would also involve determination of causation, specifically answering the question as to whether or not any observed biological effects are due to ARD-associated contaminants and, if so, which contaminants and at what concentrations.

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8.5 Closure and Long-Term Considerations

During the decommissioning phase, current environmental conditions are compared to the predictive models to assess the need for long-term monitoring. Because there may be significant lag times to the onset of ARD, the absence of ARD issues during operations does not negate the possibility of ARD conditions occurring following mine closure. If ARD releases have not occurred during operations, a reduction in monitoring frequency is typically appropriate.

If operational monitoring identified impacts to biological receptors, the objective of monitoring during decommissioning and post closure is to measure recovery in impacted areas.

Access to remote sites may be an issue during the closure and decommissioning phases. For these sites, remote monitoring techniques may be employed.

It is common in monitoring for potential ARD effects to continue well into the post-closure phase because ARD can become evident after a considerable latent period. The frequency of post-closure monitoring is typically reduced relative to the frequency during operations so post-closure often might be only once or twice per year, depending on the predictions for ARD occurrence for a particular site. Guidance on when to cease monitoring is provided in Chapter 9.

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8.6 References and Further Reading

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